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SCALE-UP MICROBIAL FUEL CELL AS A WASTE-TO-ENERGY SYSTEM FOR THE COLORADO CONVENTION CENTER

by

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Scale-Up Microbial Fuel Cell as a Waste-to-Energy System for the Colorado Convention Center.

Thesis directed by Assistant Professor Zhiyong Jason Ren.

ABSTRACT

Worldwide concerns of resource scarcity and climate change are driving the search for carbon-neutral, renewable energy alternatives for fossil fuels. Organic wastes such as food waste represent an abundant domestic resource for energy production. Recognizing the potential embedded in organic waste, various energy conversion technologies have been developed. Food waste from the Colorado Convention Center in Denver, Colorado can be used as the substrate for a microbial fuel cell (MFC) reactor, a newly developed technology that directly converts waste to energy. Microbial fuel cells (MFCs) are bio-electrochemical reactors that use microbes as biocatalysts and convert biodegradable resources into electricity. Previous lab-scale experiments using Colorado Convention Center food waste showed a sustainable power density of 155 mW/m^2 with a waste reduction of approximately 70%. Based on the encouraging preliminary data, a scaled-up version of a MFC reactor was designed and constructed as a continuous flow-through system using an air cathode. The most cost-effective materials were used to manufacture this reactor including activated carbon cloth and stainless steel current collector to test the feasibility of scaling up a MFC reactor. A new coating, polydimethylsiloxane (PDMS), was also used to

construct the scale-up MFC as a tubular reactor so that the cathode would have more efficient oxygen reduction capabilities. In addition, a fermentation chamber served as a holding tank for the scale-up MFC to assist with hydrolysis, which also helped to compare a MFC with a closed biodegradation system like anaerobic digestion. Several parameters including chemical oxygen demand (COD) loading and hydraulic retention time (HRT) were optimized to achieve the best performance. The scale-up MFC was discovered to also have a waste reduction of approximately 70%, with the highest COD removal reaching about 90% and a power density around 19 mW/m^2 or 1,865 mW/m^3. A life cycle assessment (LCA) was also conducted to compare the energy input of manufacturing the scale-up MFC with the fossil fuels displaced from its electricity generation. This was also compared to food waste sent to a landfill and composting. These results will be used to help determine the feasibility of an on-site pilot scale MFC reactor for the Colorado Convention Center.

This abstract accurately represents the content of the candidate's thesis. I recommend its publication.

Signed_______________________
Zhiyong Jason Ren

DEDICATION

I dedicate this thesis to my boyfriend for all his help and support. I also dedicate this thesis to my parents who always motivated me and encouraged me to work hard and pursue my goals.

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1. Introduction

Global concerns of environmental pollution, resource scarcity, and climate change are driving the search for carbon-neutral, renewable energy alternatives for fossil fuels. As cities try to reduce their fossil energy use and the associated carbon footprint, bioenergy from waste materials is increasingly viewed as a win-win strategy, because it offers significant economic and environmental benefits. Such strategies can simultaneously accomplish waste treatment and generate energy locally, thus reducing carbon emissions and benefiting the economy by providing jobs.

The U.S. produces 250 million tons of municipal solid waste (MSW) per year that has an energy content of 0.85 terawatts per hour (TWh). More than half of this MSW is biodegradable and can be used for bioenergy production. The U.S. EPA reports that currently more than 500 landfills have biogas utilization projects to convert landfill gas to electricity (US EPA, 2011).

Recognizing the potential embedded in organic waste, various energy conversion technologies have been developed. These technologies range from anaerobic digestion biogas energy recovery to combined heat/power systems, as well as newly developed technologies, such as microbial fuel cells (MFCs). However, the energy recovery efficiency and reduction of carbon emissions can vary from these technologies depending on the nature of the bioresource, transportation, and pre-processing that may be required.

The aim of this study was to manufacture a scaled-up microbial fuel cell (MFC) using Colorado Convention Center food waste as a substrate. This is a direct waste-to-energy reactor with the ability to power a small strand of LED lights while treating food waste. The goal was to create a sustainable food waste reduction system that will offset its carbon footprint by generating electricity. A life cycle assessment (LCA) was also prepared to calculate the amount of fossil fuels displaced from the aforementioned electricity generation compared to the amount of greenhouse gases released to manufacture the scale-up microbial fuel cell reactor. This was also compared to food waste disposal at the Denver Arapahoe Disposal Site (DADS) landfill.

1.2 Purpose of Study

Organic solid wastes such as food waste represent an abundant domestic resource for bioenergy production. New methods of energy production are being researched as a result of the rising cost and limited amount of fossil fuel supplies. Microbial fuel cells (MFCs) are a developing renewable energy system that can directly convert biodegradable resources to electricity. This process entails the use of exoelectrogenic bacteria as catalysts to degrade organic matter and transfer electrons to an electrode (Logan, 2008). Microbial fuel cells can use food waste as the organic matter that fuels the reactor. The organic matter stream flows through the anaerobic chamber that contains an anode, which provides the surface area for the bacteria to consume the substrate and deliver electrons to the anode. The cathode is positively charged and is the equivalent of an oxygen sink at the end of an electron transport chain when using an air cathode. The anode and cathode are connected with wires and a resistor to

complete the circuit (Logan, 2008). Figure 1 shows a pictorial diagram of the bio-electrochemical process of a microbial fuel cell.

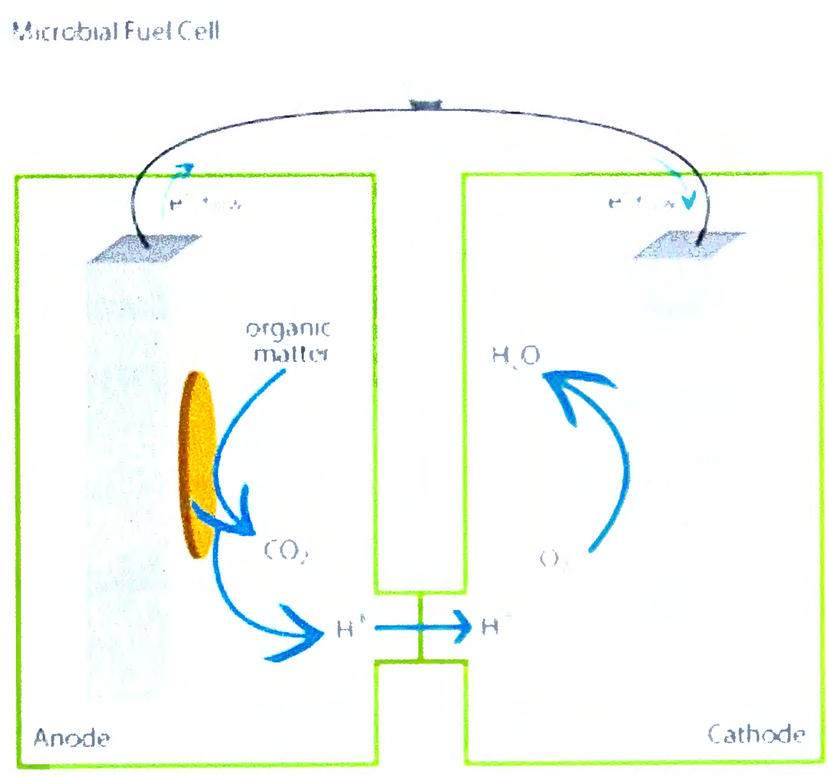

Figure 1.1: Diagram of a microbial fuel cell (Biomass Magazine, 2009)

The purpose of this study was to develop a scale-up reactor that could handle a high loading of food waste from the Colorado Convention Center. Different parameters were tested to achieve the best and most stable performance of the reactor to determine whether a pilot scale reactor would be feasible. The experiment also explored the ability of a MFC reactor to power a strand of LED lights. The final product would be a larger MFC reactor powered by food waste that could generate enough electricity to be sustainable.

1.3 Scope of Study

The scope of this research involves many factors. First, a scaled-up design was chosen to develop an on-site reactor for the Colorado Convention Center to handle their food waste. The design of the cathode was also unique in that low-cost materials were chosen to show that a cost-effective reactor could be constructed. Lastly, the reactor was operated in both fed-batch and continuous-flow modes as well as optimized by testing chemical oxygen demand (COD) loading and the different hydraulic retention times (HRTs).

1.3.1 Scaling Up Microbial Fuel Cells

In practical applications, scaling up MFCs makes sense to achieve more power in an attempt to make these reactors commercially available. To accomplish this, the reactor needs to have a high performance and be relatively inexpensive to manufacture.

Logan (2010) asserts that scale-up laboratory MFCS are those over 1 liter, where only a few studies have been done because of the continuous pumping of large volumes of medium. These studies have explored mediator- and membrane-less reactors, baffled reactors convenient for stacking, and tubular MFCs (Jang et al., 2004; Li et al., 2008; Scott et al., 2007). Due to the high surface area and exposure to oxygen, a tubular MFC design was chosen for this scale-up MFC reactor to accommodate an air cathode. The peak power performance for a scaled-up tubular MFC was shown to be 30 mW/m^2 (Scott et al., 2007).

1.3.2 Design

An air cathode was chosen for this scale-up design because the reactor would only need to have a diffusion layer that is oxygen permeable and exposed to the air. Oxygen becomes the electron acceptor and is much more inexpensive than other electron acceptors such as ferricyanide. A graphite fiber brush was chosen for the anode and a combination of activated carbon cloth, stainless steel mesh, and polydimethylsiloxane (PDMS) was chosen as the materials for the cathode. The activated carbon cloth was used as the catalyst instead of platinum to minimize the cost of manufacturing the reactor.

1.3.2.1 Stainless Steel vs. Titanium

Stainless steel and titanium were compared as current collectors for the reactor. The objective was to avoid precious metals such as platinum and titanium and to use cheaper and widely available metals such as stainless steel to manufacture the scale-up MFC.

1.3.2.2 PDMS vs. PTFE

Two different diffusion layers were tested to use as a cathode for the scale-up MFC. PTFE has been commonly used with carbon cloth to act as a diffusion layer and prevent water leakage. While this coating works well for bottle reactors and smaller reactors, it could not be water sealed on a large scale because the weave of the carbon

mesh is too loose. Zhang et al. (2010) found this also to be true. Therefore, polydimethylsiloxane (PDMS) was used for the cathode applied to stainless steel mesh. This diffusion layer material proved to be water tight when applied in a consistent fashion and is also oxygen permeable (Zhang et al., 2010).

1.3.3 Operation and Optimization

With this cost-effective design, the goal was to optimize performance to achieve the highest power density. This was tested in both fed-batch mode and continuous-flow mode. Different COD concentrations were tested to determine the optimal substrate loading as well as different HRTs were evaluated to see what the best retention time is when running this reactor continuously.

1.3.4 Life Cycle Assessment (LCA)

A life cycle assessment (LCA) was conducted to calculate the energy input and greenhouse gas emissions released to manufacture and run the scale-up MFC. A LCA is a methodology that examines the environmental impacts of a product, process, or service from beginning to end or "cradle to grave." These results were compared with fossil fuels displaced by electricity generation from the scale-up MFC, which is a carbon neutral energy source. This was also compared to other food waste disposal alternatives such as landfills and composting.

Foley et al. (2011) compared MFCs with anaerobic treatment at wastewater treatment plants with a LCA. They found that the positive environmental impact for both

technologies was the displacement of fossil-fuel based energy while the negative environmental impacts for anaerobic treatment are electricity consumption and transportation of biosolids and the negative impact for MFCs is the resource and emissions-intensive materials needed to construct the MFC. Under the IMPACT2002+LCA framework this study used, the positive benefits outweighed the negative impacts, although the uncertainty for the MFC option was high and the results were contingent on a high performance of the MFC. They state that achieving the 1000 $A \cdot m^3$ target at 0.5 V net voltage will be a major challenge (Foley et al., 2010). This is the only LCA study on MFCs that we know about thus far.

2. Scale-Up MFC Construction and Operation

The following describes the scale-up MFC construction with specific details on materials and the operation of a continuous-flow, tubular MFC with an air cathode. This includes manufacture details and literature review comparisons of different materials.

2.1 MFC Construction

The MFC consists of an anode, cathode, and various other materials to complete a circuit and generate electricity. These materials are described in detail in the following sections.

2.1.1 Cathode Structure

The materials chosen for the cathode were based on the factors of: most reliable structure, highest potential power density, and cost-effectiveness. The key element to a sustainable scale-up microbial fuel cell (MFC) reactor is the use of inexpensive materials. Scaling up a MFC reactor means an increased size of reactor and thus, more material. To make the construction of a large reactor feasible, the parts must be relatively inexpensive and widely available. To date, many microbial fuel cell reactors use platinum or titanium, which are precious metals and therefore, rare and

expensive. These help improve power density but may not be practical in the long run due to the reasons above (Logan, 2010). Therefore, these metals were avoided as catalysts and current collectors. PTFE was also considered when applied to carbon cloth as a binder, but this material is also expensive (Logan, 2010), and was not strong enough to water seal the carbon cloth, which has a loose weave (Zhang et al., 2010).

The following three materials were selected to form the cathode structure:

Zorflex® Activated Carbon Cloth (ACC): This material was chosen because of its high surface area and good adsorption capacity (Deng et al., 2009). Deng et al. (2009) found that ACC performed better than carbon felt and Pt-coated carbon paper because of its high surface area thus producing a low cathodic overpotential. The cost is also relatively inexpensive at $40 per square meter (Chemviron Carbon, FM70). A piece of activated carbon cloth is shown in Figure 2.1.

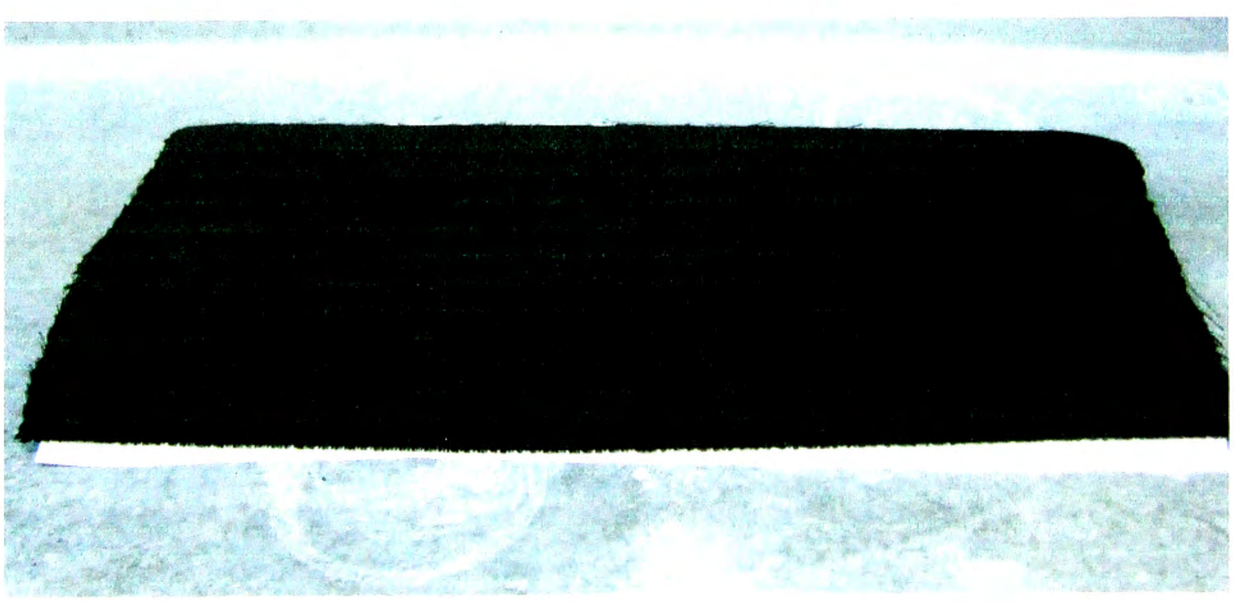

Figure 2.1: Activated Carbon Cloth

Stainless Steel Mesh: This material (Type 304, McMaster-Carr) was chosen because it has been shown to an excellent current collector. Zuo et al. (2008) found that stainless steel mesh applied to an Anion Exchange Membrane (AEM) increased the power by 28 percent. A roll of stainless steel mesh is shown in Figure 2.2.

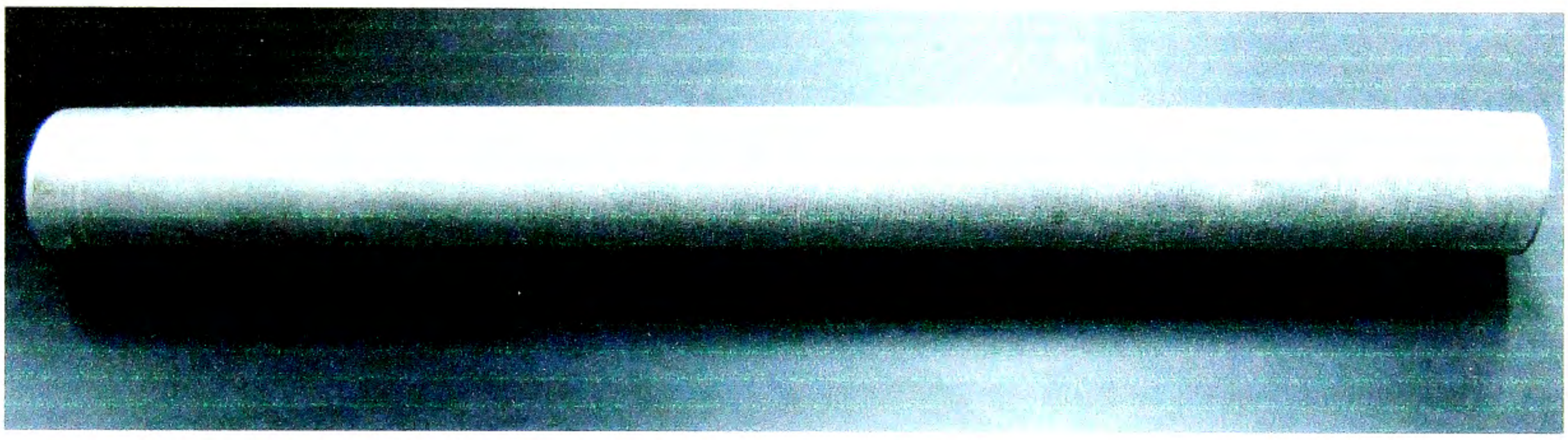

Figure 2.2: Stainless Steel Mesh

Poly(dimethylsiloxane) (PDMS): This is a 10:1 mixture of base and curing agent (Sylgard 184 Elastomer Kit, Dow Corning) used as a diffusion layer applied to the air-side of the stainless steel mesh. PDMS has a flexible Si-O structure with methyl substituents. This means that PDMS is oxygen permeable, but also highly hydrophobic therefore it is able to provide a watertight seal—unlike the PTFE coating (Zhang et al., 2010). Carbon black is also mixed with the base and curing agent for extra conductivity resulting in the black color of the coating.

The materials above and a brush anode complete the design of the tubular MFC with air cathode. The cathode structure is shown below in Figure 2.3.

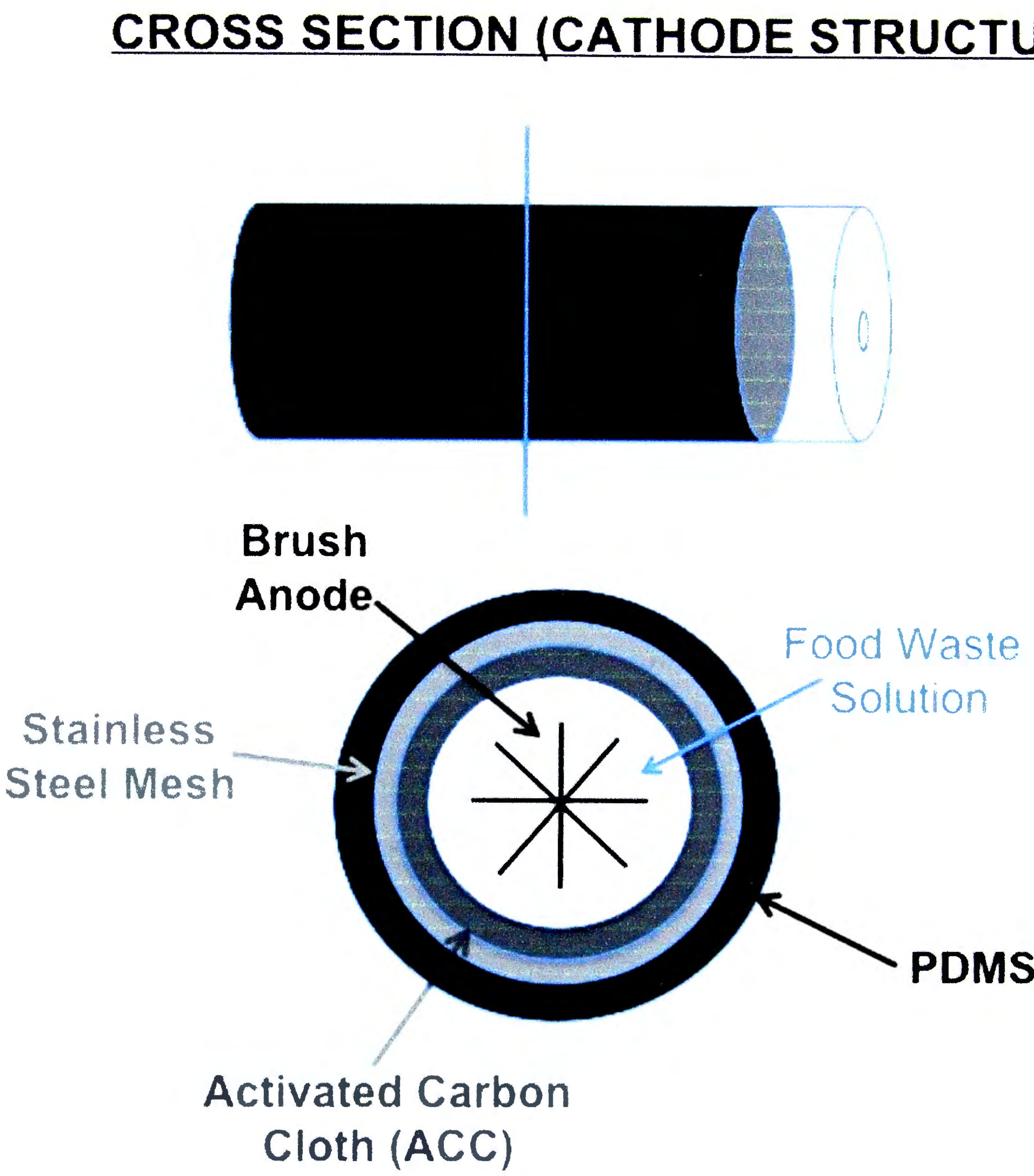

Figure 2.3: Diagram of scale-up MFC design

The activated carbon cloth is on the inside with the PDMS-coated stainless steel mesh wrapped around the cloth, which is all supported by a Plexigas cylinder with many 5/8" diameter holes. The food waste solution flows through the carbon fiber brush anode. The above design is connected with tubing (3/8" ID, Tygon Tubing) to a

holding tank (2 liters) and attached to a datalogger with a resistor in between that gives the voltage of the reactor.

2.2 Food Waste

To characterize the energy recovery potential from different residential wastes, a PhD student (K. Kronoveter) at the University of Colorado Denver collected samples from the Colorado Convention Center, Denver International Airport and Denver Botanical Gardens, and tested the wastes for direct electricity production in microbial fuel cells (see Table 2.1).

Table 2.1: Electricity production and waste reduction from different food waste samples (Kronoveter, 2010)

Sample Source	**SFW**	**CCC**	**DBG**	**DIA**	**Acetate**
Power Density (mW/m^2)	170	155	145	180	229
COD Removal (%)	74.1	73.1	69.9	74.0	73.2

SFW: Simulated Food Waste, CCC: Colorado Convention Center, DBG: Denver Botanical Garden, DIA: Denver International Airport

According to the research done above and because of the closeness of proximity, Colorado Convention Center food waste was chosen as the substrate for the scale-up MFC. Food waste was collected from a banquet on December 16, 2009. The food waste included ham, rolls, and salad with various sauces. The food waste was characterized by measuring chemical oxygen demand (COD), total solids (TS), volatile solids (VS), and fixed solids (FS). For a more thorough study on the hydrolysis and characteristics of food waste as a substrate for a MFC, please refer to K. Kronoveter's work (Kronoveter, 2010).

Pant et al (2010) did a review of other studies that have used food wastewater as the substrate for MFCs including brewery wastewater, chocolate wastewater, food processing wastewater and meat processing wastewater (Feng et al., 2008; Wen et al., 2009; Patil et al., 2009; Oh et al., 2005; Heilmann et al., 2006). The largest current density at maximum power was the chocolate industry wastewater at 1.5 W/m^2 (Pant et al., 2010; Patil et al., 2009).

2.2.1 COD

The results for COD are below (Figure 2.4). Chemical oxygen demand is an indirect measurement of the amount of organic matter in water. Food waste from the Colorado Convention Center was diluted with deionized (DI) water to create the food waste solution to be pumped into the MFC. Each point below is the average of tests done in triplicate.

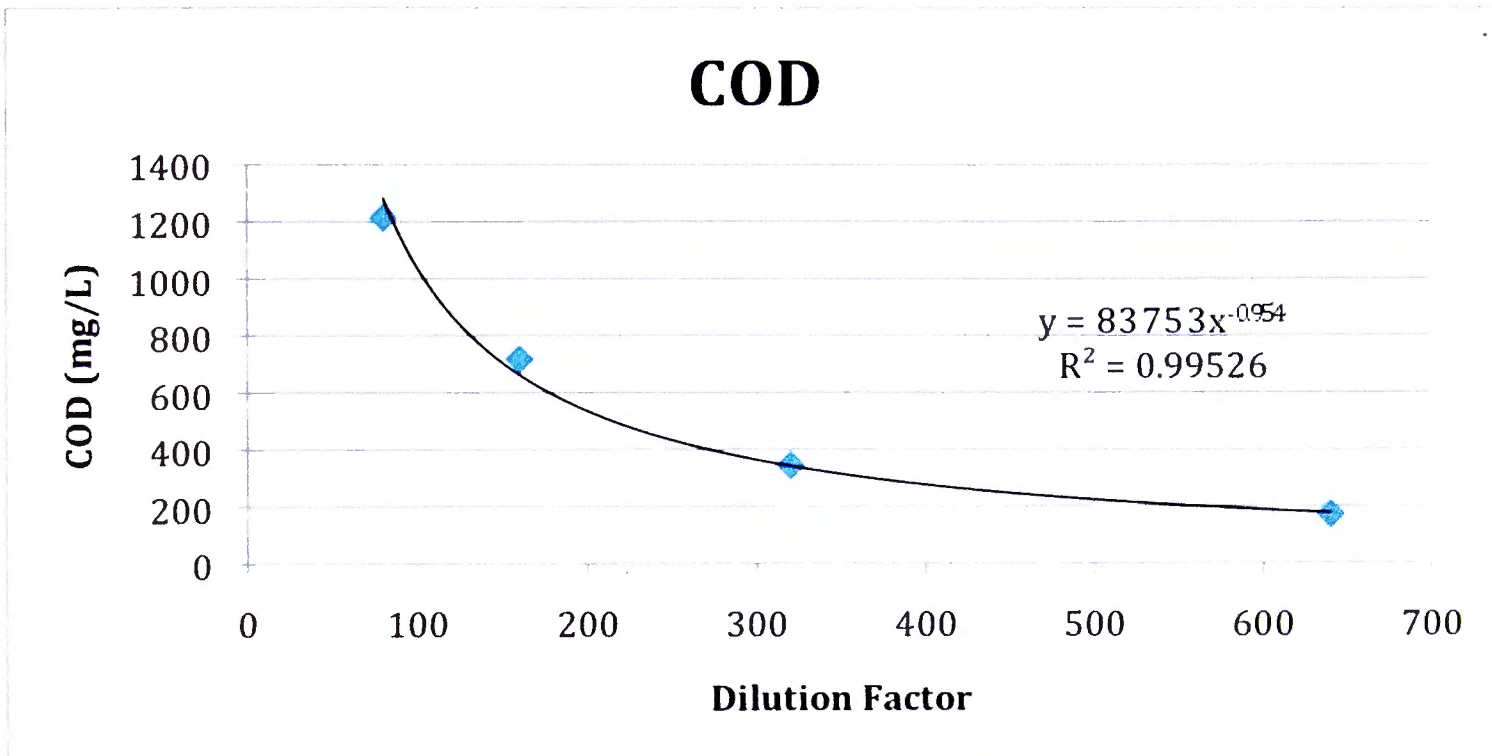

Figure 2.4: COD versus dilution factor

The COD for the food waste solution is in the optimal range when diluted by a factor of 80 to 640. The COD curve decreases by a power of negative one with an increased dilution factor because the food waste substrate is very complex. A dilution factor of in the range of 80 to 160 was chosen for most of the experiments.

2.2.2 Total Solids, Volatile Solids, Fixed Solids

The results for TS, VS, FS are below in Table 2.2.

Table 2.2: Total solids, volatiles solids, and fixed solids

Substrate	TS	VS	FS
Food Waste Solution (160x)	1.28 g/L	0.76 g/L	0.52 g/L

The above values are for a food waste solution diluted by a factor of 160; this is the dilution factor used for food waste solution in the scale-up MFC. The above parameters represent a rough approximation of the organic matter in the food waste solution.

2.3 MFC Operation

The scale-up MFC operation begins with the food waste solution in a 2-liter holding tank, which is then pumped through tubing into the 1.5-liter scale-up MFC (See Figure 2.5). The food waste is blended and then diluted with deionized (DI) water, because it is such a complex substrate and the COD would otherwise overwhelm the reactor. Another student working with food waste as a substrate has discovered that the optimal COD range for a microbial fuel cell reactor is between 500 and 1,500 mg/L (K. Kronoveter, personal communication, November 29, 2010). The following describes the inoculum, buffer solution, and fed-batch vs. continuous flow operation.

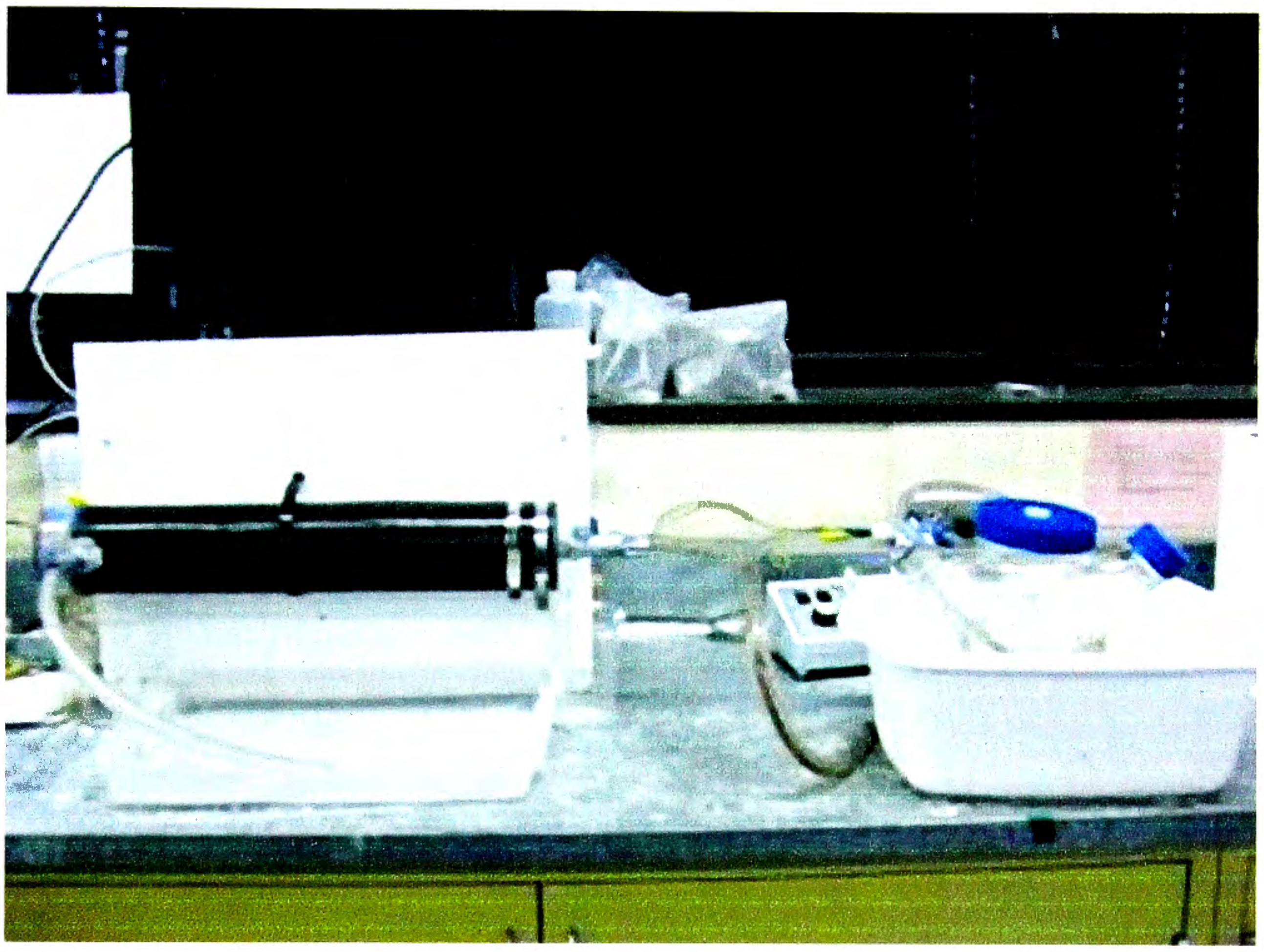

Figure 2.5: Picture of scale-up MFC set-up in lab

2.3.1 Inoculum & Medium

The food waste solution was inoculated from anaerobic digester sludge from the Littleton/Englewood Wastewater Treatment Plant in Colorado. The medium or food waste solution mainly consists of 20% sludge or solution with adapted bacteria and 80% DI water. A phosphate buffer solution was added (4.58 g/L Na_2HPO_4, 2.45 g/L NaH_2PO_4, 0.31 g/L NH_4Cl, 0.13 g/L KCl, 10 ml/L Vitamin solution, 5 ml/L Mineral solution). These are nutrients for the bacteria or microbes and also help to regulate pH. A typical pH for the final solution was about 6.68. For some experiments, 250 mg/L glucose was added to jumpstart the reactor—the substrate for these experiments is henceforth referred to as 'simulated food waste (SFW)'.

2.3.2 Fed-Batch Flow

Batch flow is the complete replacement of media once the bacteria have consumed the substrate. The food waste solution was replaced at the end of each fed-batch cycle or a voltage of approximately 20 mV. About 20-30 percent of the previous solution is retained so that the system has bacteria already adapted to food waste consumption.

2.3.3 Continuous Flow

Continuous flow is mainly characterized by the hydraulic retention time (HRT). The theoretical HRT was calculated from the volume of the medium and the flow rate into the reactor (Huang and Logan, 2008). For example, the HRT for a flow rate of 12 mL/min was calculated to be 2 hours for the scale-up MFC and 4.5 hours for the total HRT (scale-up MFC and holding tank). The total HRT for scale-up MFC and holding tank was used for conducting continuous flow experiments with recycle—we recycled the effluent of the scale-up MFC back into the holding tank.

Di Lorenzo et al (2009) found that to achieve the highest energy recovery and COD removal rate, the optimal HRT for their air cathode/disc anode stack MFC was 17 hours. In contrast, they calculated that an upflow anaerobic sludge blanket (UASB) reactor could use HRTs as low as 4-8 hours. Other MFCs were operated at HRTs of anywhere from 2.13 hours (Wen et al., 2010) to 24 hours (Zuo et al., 2007).

3. Preliminary Data

The data below informed the decision on which materials to use for the scale-up MFC reactor. This data was gathered using a microbial fuel cell bottle reactor which as a volume of 250 milliliters (See Figure 3.1). Bottle reactors are operated in fed-batch mode.

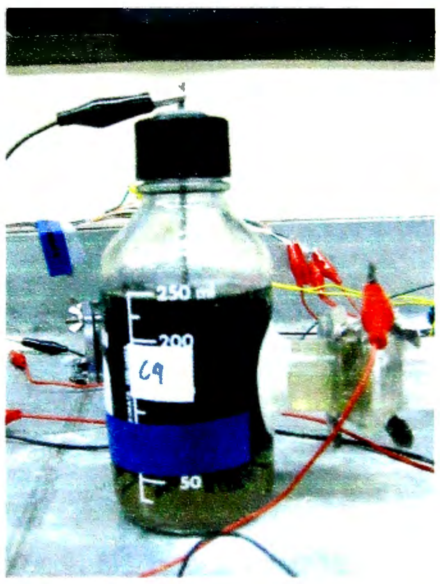

Figure 3.1: Bottle reactor with brush anode

3.1 Titanium vs. Stainless Steel

The first decision we made based on preliminary data was which metal to use for current collection. The voltage results were very similar—both voltage profiles showed a stable performance around 0.4 volts. The external resistance used for the bottle reactors was 1,000 Ohms.

Stainless steel mesh was chosen as the current collector for the scale-up MFC because it has the same performance as a titanium rod and is a less expensive metal. The cost of type 304 stainless steel mesh is less than $50/m^2 (Zhang et al., 2010) and can be used as an integral part of the microbial fuel cell cathode by wrapping it around the Plexiglas cylinder and coating it with polydimethylsiloxane (PDMS).

3.2 PTFE vs. PDMS

The bottle reactor results for PTFE on stainless steel mesh versus the PDMS on stainless steel mesh bottle reactor results are below (Figure 3.2).

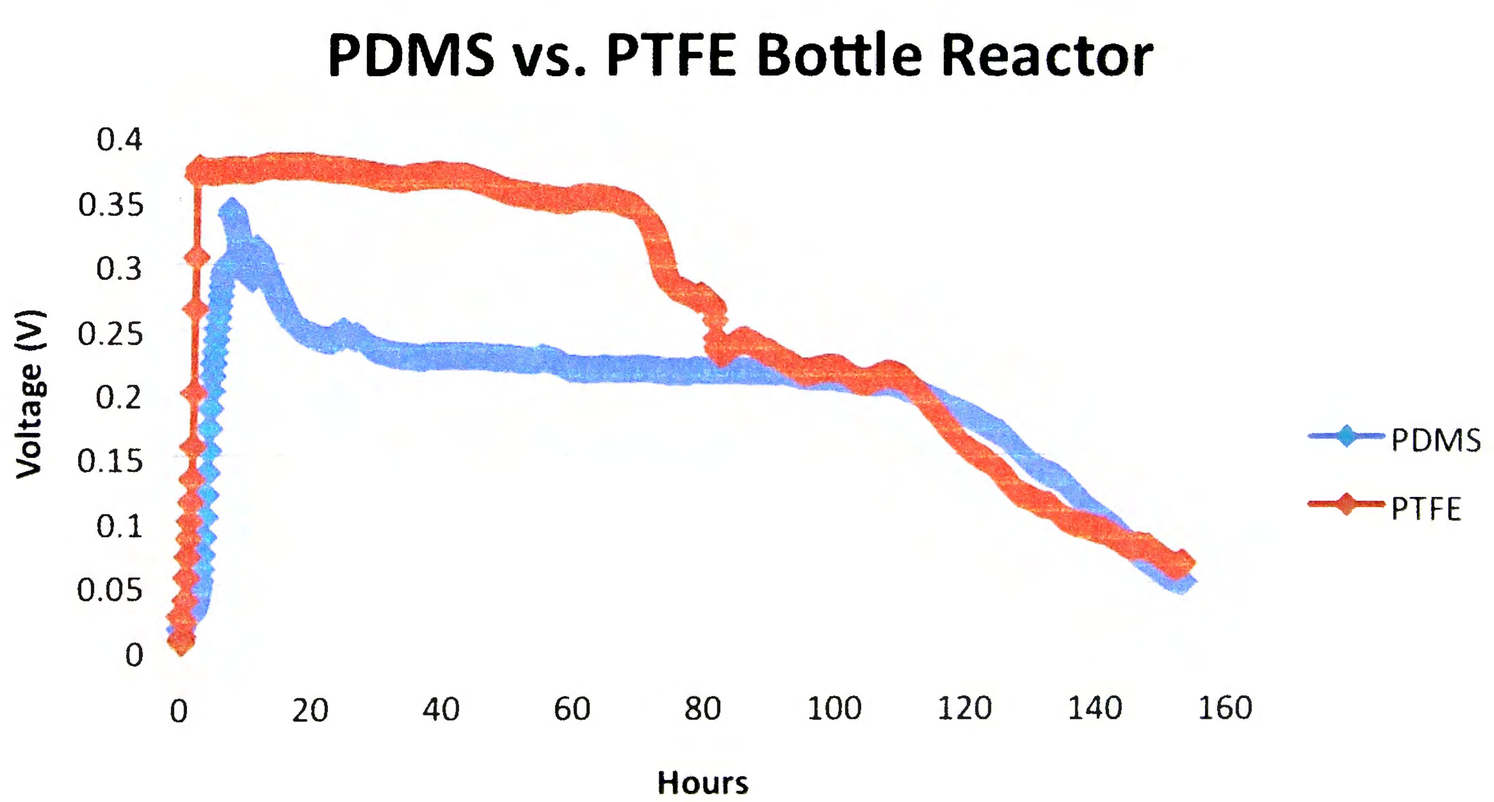

Figure 3.2: Voltage profile for bottle reactors with PDMS and PTFE on stainless steel mesh

The bottle reactor with PDMS on stainless steel mesh reached a maximum voltage of 0.35 V and kept a steady 0.2-0.25 V for 120 hours (5 days). This is similar to PTFE on stainless steel mesh but not as high of voltage. However, PDMS was chosen for the scale-up MFC reactor because of its ability to be a watertight coating over a large surface area. In addition, PTFE is a more expensive binder at an average of $60/m^2 (Logan, 2010) as opposed to PDMS, which has an estimated cost of $0.13/m^2 (Zhang et al., 2010).

3.3 Activated Carbon Cloth vs. Platinum-Coated Carbon Cloth

Another innovative material being used for oxygen reduction is activated carbon cloth instead of a platinum catalyst. Activated carbon does not reduce oxygen as well as a platinum coating, but its high surface area makes up for this by being a useful material for MFCs where the current densities per electrode area are low (e.g. a scaled-up MFC reactor). Also, platinum is a very expensive precious metal not suitable to scale-up, while activated carbon cloth costs $40/m^2 (P. Morgan, Chemviron Carbon, personal communication, February 15, 2010). Compared to the carbon cloth usually used for MFC applications with a cost of approximately $1,000/m^2 (Zhang et al., 2010), activated carbon cloth is clearly a much more cost-effective choice for a scale-up MFC.

3.4 Fermentation

Fermentation is the process of anaerobic bacteria degrading a substrate to yield the end products of methane (CH_4) and carbon dioxide (CO_2). Logan et al. (2006) states

that in a MFC, bacteria will use the substrate for fermentation and/or methanogenesis if the bacteria are unable to use the electrode as an electron acceptor.

Other studies using a fermentation process in concert with a MFC include a carbon monoxide fermentation chamber with MFC (Kim and Chang, 2009) and a process combining dark fermentation, MFCs and a microbial electrolysis cell (MEC) for hydrogen production (Wang et al., 2011).

The holding tank is technically a fermentation chamber since there are microbes in this tank as well and the process of fermentation takes place in a closed chamber yielding methane and carbon dioxide. To characterize the amount of methane and carbon dioxide in the holding tank and headspace of the scale-up MFC, a sample of gas was taken after the media had been changed and the MFC was running for a few days. This sample was taken with a 100 µl syringe and analyzed by gas chromatography (GC). The results can be seen in Table 3.1.

Table 3.1: Percentage of methane and carbon dioxide in holding tank and scale-up MFC

	CH_4	**CO_2**	**Other gases**
Holding Tank	~78%	~22%	N/A
Scale-Up MFC	~71%	~20%	~9%

The holding tank headspace is comprised of approximately 78 percent methane and 22 percent carbon dioxide. The scale-up MFC is similar in that its headspace consists of 71 percent methane and 20 percent carbon dioxide. Other gases were also detected in the scale-up MFC headspace—a hypothesis is that this could be hydrogen. COD samples were also taken periodically from the holding tank. The COD gradually

declined in the holding tank from the process of fermentation. The fermentation process would have 70 percent removal in about a week. The food waste solution only would stay in the holding tank for a maximum of one day in this study, so the fermentation process was assumed to have little to no effect in the holding tank. Microbial fuel cells can remove COD at a much faster rate as can be seen in the next chapter (Also see Appendix A).

4. Results

The following describes the preliminary results and calculations, COD optimization results, and HRT results.

4.1 Baseline Measurements and Calculations

The polarization and power density curves are necessary to calculate the end results and give us a depiction of the reactor's performance at various external resistances. The polarization curve compares voltage with current density while the power density curve compares power density with current density.

4.1.1 Polarization and Power Density Curve

Below are the polarization and power density curves used to determine the optimal external resistance for the scale-up MFC reactor in Figure 4.1. These were conducted in batch mode.

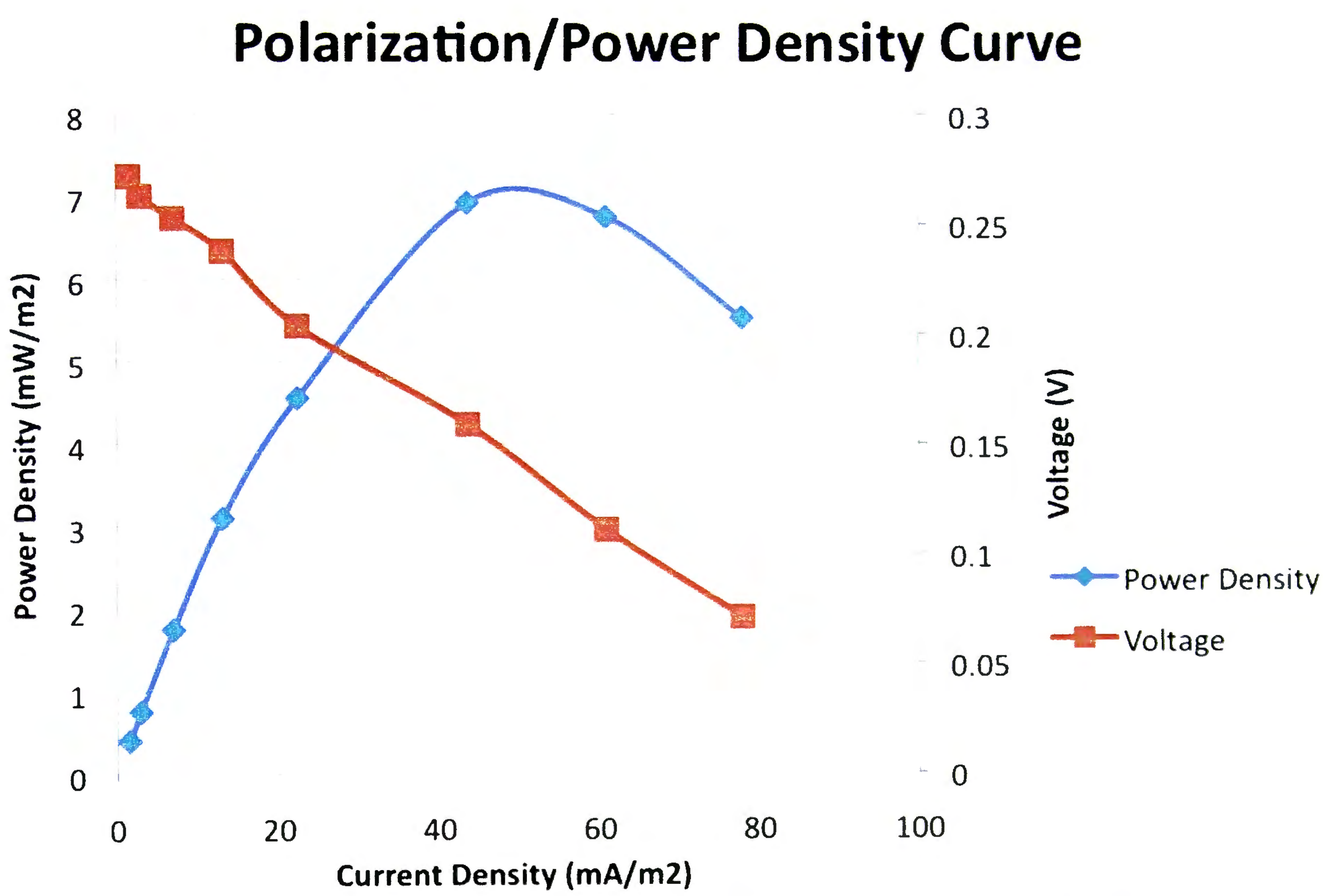

Figure 4.1: Polarization and power density curve for scale-up MFC

As seen in Figure 4.1, at the highest power density, the optimal external resistance for the maximum power density turned out to be 50 Ohms. This external resistance was used in the following experiments.

4.1.2 Calculations

Several formulas are used to calculate the results for the scale-up MFC. These parameters assist with evaluating the performance of a MFC. First, percent COD removal is calculated from the influent and effluent COD (mg/L).

$$\% \, COD \, Removal = \frac{Influent \, COD - Effluent \, COD}{Influent \, COD} \tag{1}$$

Then, the maximum power density (mW/m^2 or mW/m^3) is determined by the formula below. The power can either be normalized by cathode surface area (SA) or volume of wastewater (V). E stands for voltage (Volts) and R is resistance (Ohms).

$$Power \, Density = \frac{E^2 / R}{SA \, or \, V} \tag{2}$$

Coulombic efficiency (CE) is the measurement of how well electrons are transferred in an electrochemical reaction. The formula for fed-batch mode is below.

$$CE = \frac{8 \int I \cdot dt}{F \cdot \Delta COD \cdot V} \tag{3}$$

CE is the integral of current or I (ampere) over time (s) divided by the Faraday's constant (F) times the change in COD (g/L) times the volume of wastewater (L). Faraday's constant is 96,485 coulombs, where 1 coulomb equals 1 ampere times 1 second.

$$CE = \frac{8 \cdot I}{F \cdot \Delta COD \cdot \dot{V}} \tag{4}$$

The coulombic efficiency above is the equation used for continuous flow mode. V_dot is the volumetric flow rate (L/s).

4.2 Simulated Food Waste

Experiments with simulated food waste (SFW) or food waste plus 250 mg/L glucose were conducted to jumpstart the scale-up MFC and to help acclimate the microbes to a MFC with food waste as the substrate. These experiments had a different polarization and power density curve and used an external resistance of 1,000 Ohms. Therefore, the results for these SFW experiments can be found in Appendix A (Table A.1) since they are incongruous with the rest of the results in this section and unnecessary to be included in the discussion of the scale-up MFC using food waste as the substrate. The following experiments use pure food waste in the solution for the reactor.

4.3 COD Optimization

Based on the data collected for food waste characterization, food waste was diluted with DI water to reach certain COD concentrations for the influent to the scale-up MFC reactor. The different COD loading experiments were conducted in batch mode.

Table 4.1: Results for different influent COD concentrations

Influent COD (mg/L)	Effluent COD (mg/L)	COD Removal (%)	Max Power Density (mW/m^2)	Coulombic Efficiency (%)
763	166	78.2	10.31	7.30
1229	105	91.5	11.91	6.94
1420	216	84.8	15.28	6.48
*2085	263	87.4	19.44	2.11

*Hach spectrophotometer can only test COD up to 1500 mg/L so this is a rough estimate provided by the analyzer

Table 4.1 shows the COD removal, max power density, and coulombic efficiency for several different influent COD concentrations. The influent COD of 1229 mg/L had the highest COD removal, but all of the COD removal percentages were around 80-90%. The highest power density was at a COD of 2085 mg/L, but we cannot say for sure that this is the correct value since the instrument only accurately reads to a COD of 1500 mg/L. Therefore, we can assume that a COD above 1500 mg/L had the highest power density, but its coulombic efficiency was the lowest. The correlation between the max power density and coulombic efficiency for each influent COD concentration is shown below in Figure 4.2.

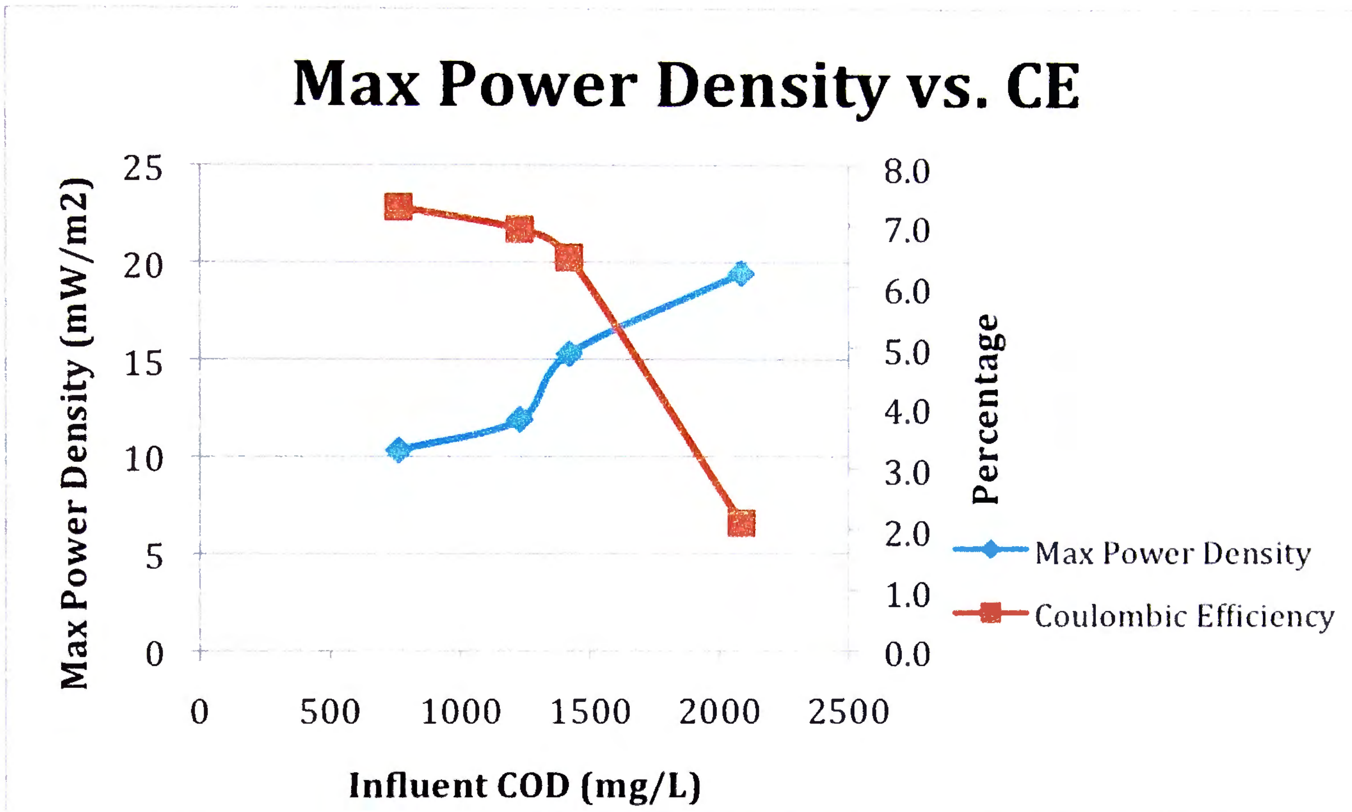

Figure 4.2: Maximum power density versus coulombic efficiency for different influent COD concentrations

The highest power density with a relatively high coulombic efficiency was the influent COD concentration of 1420 mg/L, so we can conclude that the optimal influent COD concentration is around 1400-1500 mg/L. The maximum power density reached was 19 mW/m^2.

4.4 HRT Optimization

The following results determine the optimal HRT for the scale-up MFC and the methane gas generated from this ideal HRT was calculated and added to the total power generation.

4.4.1 HRT Results

The scale-up MFC was operated in continuous flow mode to determine the ideal hydraulic retention time (HRT). The HRT is the volume of the reactor (1.5 L) over the flow rate so the faster the flow rate and water moves through the MFC reactor, the lower the HRT. The results of these experiments at varying HRTs can be seen below in Table 4.2. There was an average influent COD of 1224 mg/L.

Table 4.2: Results for different hydraulic retention times

HRT (hrs)	Flow Rate (mL/min)	% COD Removal	Max Power Density (mW/m^3)	CE (%)
2	12	65.9	1600.7	0.7
3	8	69.4	1815.1	0.6
4	6	74.6	1865.0	0.6
8	3	69.9	1825.3	0.6
16	1.5	67.6	1222.3	0.5

The 4-hour HRT has the highest maximum power density (1865 mW/m^3) closely followed by the 8-hour and 3-hour retention times. The 4-hour HRT also had the highest COD removal, although the percent COD removal for all of the HRTs were around 70%. Also, the coulombic efficiency (CE) for all of the experiments was about the same with a downward trend from the 2-hour HRT to the 16-hour HRT. A 24-hour HRT would have a flow rate of 1 mL/min so one could assume that it is similar to fed-batch mode or the COD optimization results.

The graph below (Figure 4.3) shows a comparison of percent COD removal and maximum power density in mW/m^3. One axis shows max power density and the other shows the percentage of COD removal for the HRT.

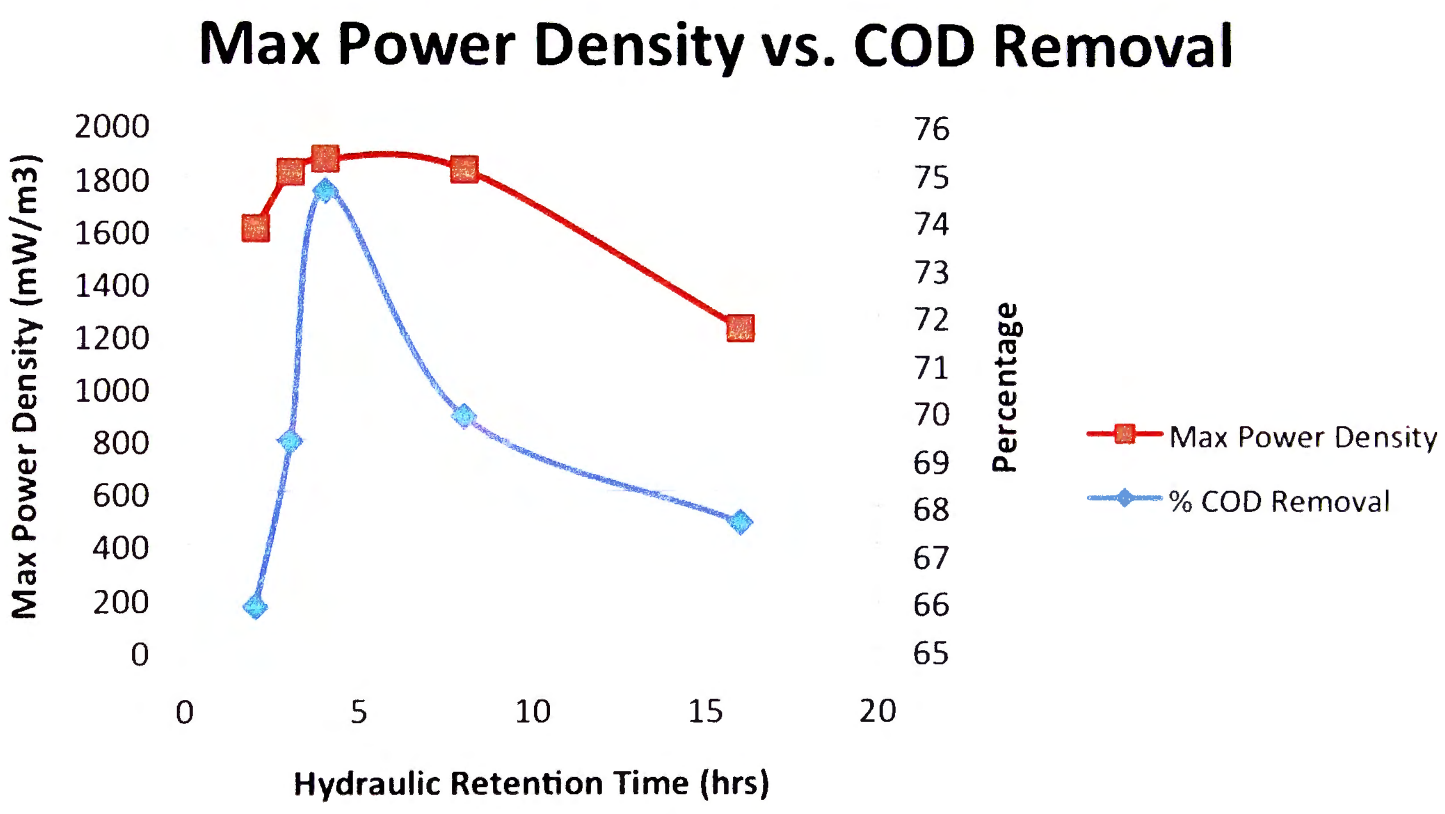

Figure 4.3: Maximum power density vs. COD removal for different HRTs

Since the 4-hour retention time has the highest power density and COD removal, it seems that the ideal HRT would be around 4 hours. Or perhaps a range of 3 to 8 hours could be used. It was noted that the longer the HRT, the more time the reactor should have had for COD removal, but this was not the case. This may be the result of the uncertainty of influent COD concentration to effluent COD concentration, which varies throughout the continuous flow experiments. With a higher HRT than 4 hours, the power density decreased along with COD degradation; this may be due to the accumulation of recalcitrant substrate such as cellulosic material in the reactor that

inhibited continued microbial activity for electricity production. Since the coulombic efficiencies are all about the same, this study found that the 4-hour HRT is the optimal HRT, because a lower HRT is preferred so more food wastewater can be treated in less time.

4.4.2 Methane Production of Scale-Up MFC

Since the optimal HRT is 4 hours, the amount of methane generated in the headspace was measured. The volume of the headspace was multiplied by the change in percentage of methane in the headspace per hour as seen below in Table 4.3.

Table 4.3: Methane production in scale-up MFC

Hour	Percent Methane	Volume of Gas Generated (scf)
1	0%	0
2	24%	0.0097
3	42%	0.0073
4	57%	0.0061
	TOTAL	**0.023**

Using the EPA-recommended value for methane heat content of 1,012 Btu/scf methane (US EPA, 2011) and assuming a 33% efficiency converting the energy of a gas to electricity, the amount of electricity generated in 4 hours equals 0.0022 kWh. This means that the amount of electricity from methane production the scale-up MFC could produce in one day would be approximately 0.0132 kWh. These results are used in the following LCA comparing a scale-up MFC to the DADS landfill.

5. Life Cycle Assessment for Scale-Up MFC

The life cycle assessment (LCA) for this project will consist of a life cycle energy analysis that compares the energy input to manufacture the scale-up MFC and the energy output of the MFC, or the amount of fossil fuels the MFC displaces—this is measured by greenhouse gas emissions (GHGs). If we assume that any methane produced will also be used as a source of energy, then a microbial fuel cell reactor is a zero carbon source of energy. This will be compared to transporting the food waste to the DADS landfill as an off-site food disposal option.

The DADS landfill is a regional MSW landfill owned by the City and County of Denver and operated by the Waste Management of Colorado, Inc. DADS accepts 12,000 tons of waste per day or 3.7 million tons per year (City of Denver, 2011). The DADS landfill along with the closed Lowry landfill produce methane gas to power the 3.2 MW energy recovery plant. The DADS landfill has 150 gas wells and generates 1,000 standard cubic feet per minute (scfm) of landfill gas (Colorado SWANA, 2009).

5.1 Boundaries of LCA

The functional unit to compare the scale-up MFC with the DADS landfill and boundaries for both systems are discussed below. Then the energy inputs and outputs are compared to determine the efficiencies of both systems.

5.1.1 Functional Unit

In a LCA, the definition of the functional unit is how the outputs of the product systems are defined. The functional unit for this LCA is the change of COD per kilogram food waste. Percent COD removal is the measurement of how much organic matter the system has degraded. The timeframe chosen is one year, although the scale-up MFC removes COD in less time than the landfill. The amount of energy produced (or GHG emissions displaced) will be the environmental parameter evaluated.

5.1.2 System Boundaries of Scale-Up MFC and DADS Landfill

In this particular life cycle energy analysis, we did not include all small parts/materials of the scale-up MFC (or landfill) that are not essential to the operation (e.g. tubing connectors for the scale-up MFC). This includes secondary containment and waste materials that were reused as a part of manufacturing the scale-up MFC, that would have been disposed of anyway. Therefore, the life cycle assessment for the scale-up MFC and DADS landfill can be considered a 'cradle-to-use' assessment neglecting environmental impacts of the end products. There are so many small parts to a MFC that it would be hard to accurately portray the amount of energy consumed by the transport of each individual piece to the place of construction. The exact amount of energy needed to construct and operate a landfill is also hard to come by so this process is also simplified to only include the main processes.

Figure 5.1 shows the system boundaries of the scale-up MFC and the DADS landfill. For the scale-up MFC, the effluent is recycled to dilute the blended food waste (shown in blue arrows) and is pumped back into the reactor. The energy inputs of the scale-up MFC are mixing and pumping power while the outputs are biogas and electricity (shown as black arrows).

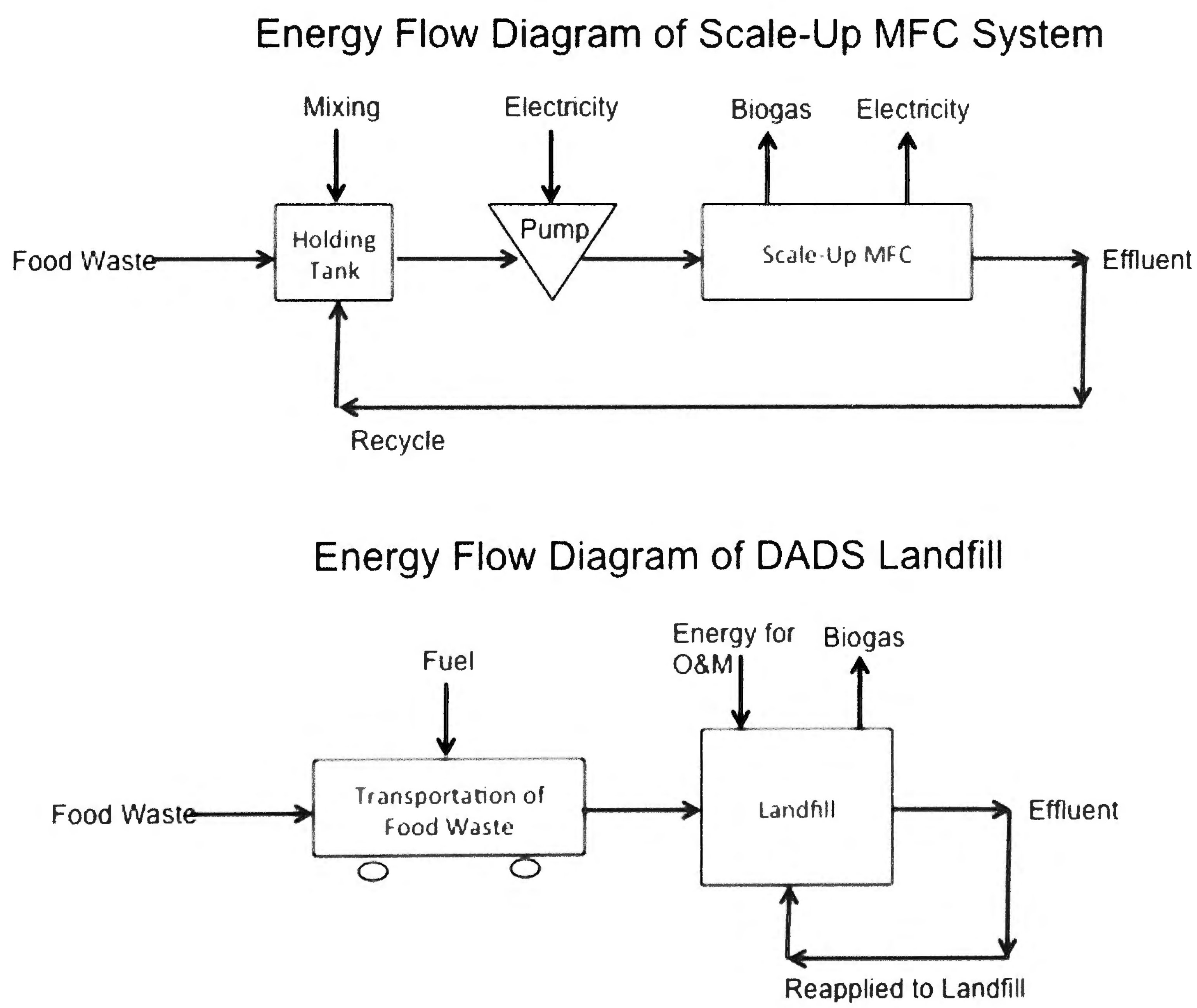

Figure 5.1: System boundaries of scale-up MFC and DADS landfill

The system boundaries of the DADS landfill include transportation of waste off-site to the landfill plus the construction and O&M costs for the landfill. The effluent is tested for heavy metals and other hazardous chemicals and is then reapplied to the landfill for maintenance purposes (D. Nyiro, DADS Landfill, personal communication, April 8, 2011). The energy output of the landfill is biogas production which is converted to electricity and sold to the local community.

5.2 Nominal Output/Input Energy Efficiencies

The nominal efficiencies of the DADS landfill and the scale-up MFC were calculated as a baseline and a starting point to compare the two systems as can be seen in Table 5.1. The energy content of food waste is estimated as 5.2 million Btu/short ton (US EIA, 2007). This is used to calculate the energy input. The energy output is calculated by converting electricity to primary energy (dividing by 33% or the efficiency of a power plant). The energy input and outputs are all standardized as primary energy, or energy from primary sources such as coal, oil, and natural gas.

Table 5.1: Nominal output/input energy conversion efficiencies for the DADS landfill and scale-up MFC

	Primary Energy Input	**Assumptions**	**Primary Energy Output**	**Efficiency**
DADS Landfill	2.7×10^{12} Btu per year	Denver Arapahoe Disposal Site (DADS) receives 3.7 million short tons of total MSW per year, of which ~14% is easily biodegradable food waste (US EPA, 2011), with an energy content of 5.2×10^{6} BTU/ton	2.6×10^{10} Btu per year*	**0.96%**
Scale-Up MFC	6.3×10^{4} Btu per year	Assuming 11 kg per year of food waste with an energy content of 5.2×10^{6} BTU/ton	4.98×10^{4} Btu per year*	**79%**

**References: Colorado SWANA, 2009 and experimental data (see Chapter 4)*

The efficiency is the energy output over the input. The energy output of the two systems neglects the O&M energy requirements for both systems. Energy is defined as primary energy (electricity divided by 33%) for both inputs and outputs.

The efficiencies above include a steady state assumption where we assume that the input of food waste into the system directly affects the energy output of the system. The following graph (Figure 5.2) shows the assumption of steady state for the two systems.

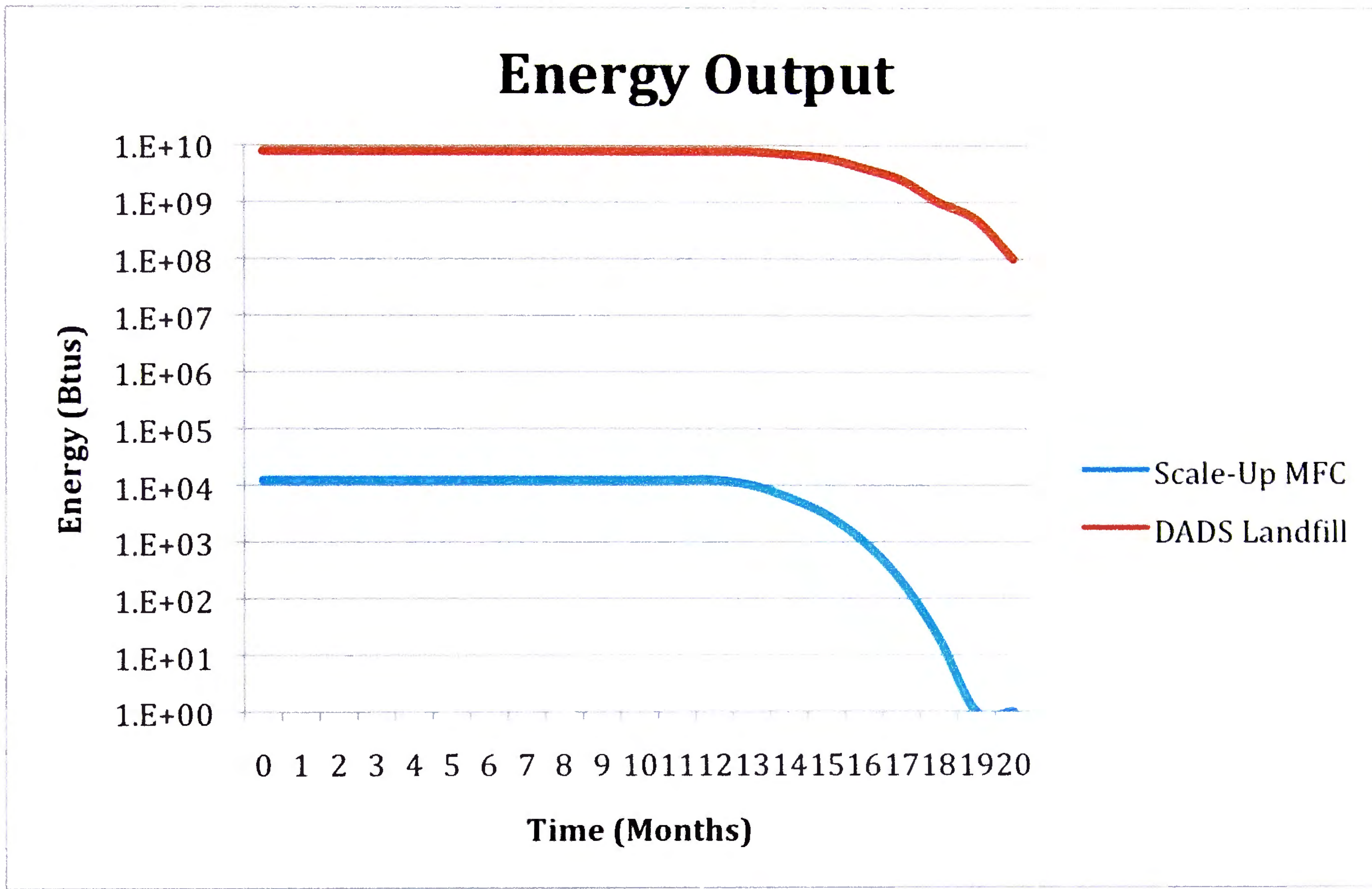

Figure 5.2: Theoretical energy output for scale-up MFC and DADS landfill if energy input ceased at one year

If the food waste or energy input ceased after 12 months, both systems would have a gradual drop-off of energy output. Since the scale-up MFC is not as large as the landfill and does not have as much waste input, the energy output would decrease faster.

5.3 Life Cycle-Based Energy Efficiencies

A life cycle inventory aggregates all system-wide inputs and outputs from producing a certain product or process. This was modified for this project to only include energy to evaluate the primary energy output/input efficiencies. Life cycle-based energy

efficiencies were done for the scale-up MFC and the Denver Arapahoe Disposal Site (DADS) landfill for comparison.

5.3.1 Life Cycle-Based Energy Efficiency for DADS Landfill

The timeframe for a life-cycle based energy efficiency for the DADS landfill was one year. This was used to calculate the energy input released by calculating the economic value of food waste disposal over this time period and then using the 2002 Purchaser Price Model of the Economic Input-Output Life Cycle Assessment (EIO-LCA) tool created by Carnegie Mellon University.

The life cycle inventory for the DADS landfill includes an estimated capital construction cost of 42 million dollars over an operational lifetime of 25 years (US EPA, 2000) and an estimate of $2 to $5 per ton O&M costs for the DADS landfill (D. Nyiro, DADS Landfill, personal communication, April 8, 2011) as can be seen in Table 5.2. The transportation was estimated by the EPA Waste Reduction (WARM) Model with an input of 518,000 tons or the amount of food waste in DADS landfill per year (US EPA, 2010).

Table 5.2: Life cycle-based output/input energy conversion efficiency for the DADS landfill

Primary Energy Input		**Assumptions**	**Primary Energy Output (Btu per year)**	**Efficiency**
Life Cycle Activities	***Energy Input (Btu per year)***			
Food Energy Content	2.7×10^{12}	See Table 5.1	2.6×10^{10}	**0.96%**
Transportation	2.0×10^{10}	EPA WARM Model (20-mile distance)		
O&M (EIO-LCA Sector #562000: Waste management and remediation services)	7.6×10^{9}	Average of $3.50 per ton (D. Nyiro, personal communication)		
Capital Construction (EIO-LCA Sector #230103: Other nonresidential structures)	1.4×10^{9}	Annualized value ($1.3 million in 2011$) with discount rate of 10% for an operational lifetime of 25 years x 14% food waste		
TOTAL	$\mathbf{2.7 \times 10^{12}}$			

The economic value of each of these sectors was converted to 2002$, multiplied by 14% (EPA-estimated food waste percentage in landfills) and used in EIO-LCA to calculate the total primary energy input of the landfill. The energy output is from methane recovery from the DADS landfill (Colorado SWANA, 2009) also multiplied by 14%. The electrical power output from the landfill was divided by 33% efficiency to calculate the primary energy output (Btu per year) above.

Different sectors of EIO-LCA were used to calculate the energy input from a landfill (Carnegie Mellon, 2011). This included construction and O&M for the landfill as well as the energy to transport the food waste to an off-site facility. The energy efficiency of output versus input is the same as the nominal output/input energy conversion efficiency (See Table 5.1).

5.3.2 Economic Analysis of Scale-Up MFC

Table 5.3 shows the cost in 2011 dollars of the materials used to construct the scale-up MFC.

Table 5.3: Economic analysis of materials used to manufacture scale-up MFC

Material	**Size/Amount**	**Estimated Cost ($2011)**	**Manufacturer**
Plexiglas (Thermoplastic)	~500 grams	$104	Colorado Plastics
Activated Carbon Cloth	1 square foot	$4	Chemviron Carbon
Stainless Steel Mesh	1 square foot	$78	Mcmastercarr.com
PDMS (Adhesive, similar to glue)	250 mL	$50	Dow Corning, Inc.
Carbon Black	2 grams	$1	Fuel Cell Store
Graphite Fiber Brush	2" x 20" brush	$85	Gordon Brush
Tubing	4 feet	$10	Tygon Tubing
Acetone (Plus other chemicals)	1 Liter	$22	Fisher Scientific Inc.
Food Waste	2,360 cm^3	$0	Colorado Convention Center
Pump	Medium Flow	$207	Control Company
TOTAL		**$561**	

Approximately \$560 was spent to manufacture a scale-up MFC with holding tank for a continuous flow system with a capacity of about two liters. A pilot scale MFC would be an on-site system.

This cost compared to costs associated with landfill disposal and composting will be discussed in Chapter 6.

5.3.3 Life Cycle-Based Energy Efficiency for the Scale-Up MFC

The Economic Input-Output Life Cycle Assessment (EIO-LCA) was used for all materials. This model considers an entire economy, or all activities of all industry sectors, to estimate the material or energy resources consumed by that industry sector. In this way, a specific industrial sector was chosen to estimate the energy and greenhouse gas emissions of a certain material (Carnegie Mellon, 2011). To use EIO-LCA, all 2011 prices were converted to 2002\$ by dividing by a factor of 1.212 (Sahr, 2010). The dollar amounts in Table 5.3 were converted to 2002 dollars to use in the EIO-LCA purchaser price model. An example of the EIO-LCA cradle-to-gate calculation is shown in Appendix B (Table B.1). The total energy input by manufacturing and operating the scale-up MFC is shown in Table 5.4 assuming an operational lifetime of one year.

Table 5.4: Primary energy input of materials and processes used to manufacture and operate the scale-up MFC

Construction/Materials	**Size/Amount**	**Purchaser Price (2002$)/Time**	**Primary Energy (Btu per year)**
Plexiglas (Thermoplastic)[1]	~500 grams	$85.81	3.2×10^6
Activated Carbon Cloth[2]	1 ft^2 (~20 g)	$3.67	5.4×10^4
Stainless Steel Mesh[3]	1 ft^2 (~200 g)	$64.36	1.9×10^6
PDMS (Adhesive, binder)[4]	250 mL	$41.25	6.7×10^5
Carbon Black[5]	2 grams	$0.83	3.8×10^1
Graphite Fiber Brush[6]	2" x 20" brush	$70.13	2.8×10^6
Tubing[7]	4 feet	$8.25	9.5×10^4
Acetone (Plus other chemicals)[8]	1 Liter	$18.15	7.1×10^5
TOTAL			**9.4×10^6**
O&M - Blending Food Waste[9]	300 W	20 seconds	1.7×10^1
O&M - Pumping[10]	4.8 W	1 year	4.3×10^5

1. EIO-LCA Sector #325211 (Plastics material and resin manufacturing)
2. EIO-LCA Sector #313210 (Broadwoven fabric mills)
3. EIO-LCA Sector #331110 (Iron and steel mills)
4. EIO-LCA Sector #325520 (Adhesive manufacturing)
5. EIO-LCA Sector #325182 (Carbon black manufacturing)
6. EIO-LCA Sector #331110 (Iron and steel mills) Carbon Fiber/Titanium Steel - Assume carbon fiber manufacturing is similar
7. EIO-LCA Sector #326220 (Rubber and plastics hose and belting manufacturing)
8. EIO-LCA Sector #325190 (Other basic organic chemical manufacturing) - Includes all chemicals added to food waste solution
9. Average power of a blender (ABS Alaskan, 2011)
10. Peristaltic pump (12 V, 0.4 A)

The above table gives the total energy input in Btu per year to manufacture and operate the scale-up MFC.

Table 5.5 compares the energy produced from the scale-up MFC with the values generated from Table 5.4. The measurements for the highest amount of electricity output were calculated in Chapter 4 and divided by 33% efficiency to determine primary energy output.

Table 5.5: Life cycle-based output/input energy conversion efficiency for the scale-up MFC

Primary Energy Input		**Assumptions**	**Primary Energy Output (Btu per year)**	**Efficiency**
Life Cycle Activities	***Energy Input (Btu per year)***			
Food Energy	6.3×10^4	See Table 5.1	4.98×10^4	**0.50%**
Transportation	0	On-site facility		
O&M - Mixing	1.7×10^1	Blending food waste (See Table 5.3)		
O&M - Pumping	4.3×10^5	See Table 5.3		
Construction-Materials (Various Sectors of EIO-LCA)	9.4×10^6	See Table 5.3, Assuming an operational lifetime of one year		
TOTAL	$\mathbf{9.9 \times 10^6}$			

Since the power (3.2 mW) of the scale-up MFC is so small, the embodied energy calculated by the comprehensive LCA is a lot larger. The longer the reactor runs though, the more electricity (and methane gas) will be generated so if there were a longer timeframe, the scale-up MFC would produce more energy.

5.4 Energy/COD Removal of Scale-Up MFC vs. DADS Landfill

Since the embodied energy or energy input of both of these systems vastly overwhelms the energy output or energy produced, we will just compare the energy production of each system against COD removal. Table 5.6 shows the primary energy (in kilojoules) over kilograms COD removed by the scale-up MFC versus the primary energy generated by food waste from the DADS landfill over kg COD removed from this waste.

Table 5.6: Comparison of primary energy output per kilogram COD removal

Scale-Up MFC	**DADS Landfill**
(kJ energy produced/ kg COD removed)	*(kJ energy produced/ kg COD removed)*
6,860	84.3

The DADS landfill calculation used the amount of primary energy produced in one year divided by the amount of COD treated in one year at a 70% removal rate. The scale-up MFC calculations used the amount of primary energy produced in one year over the amount of COD treated in one year, which was significantly higher than the DADS landfill. Therefore, the amount of GHG emissions displaced per kilogram COD removed would also be much higher for the scale-up MFC.

6. Discussion

The following provides a discussion on the results of the scale-up MFC experiments and the comparison between a MFC system with food waste and disposal of food waste in the DADS landfill.

6.1 Scaling Up a Microbial Fuel Cell

Figure 6.1 shows a Christmas tree with LED lights powered by microbial fuel cells. Dr. Jae Do Park, Electrical Engineer, experimented with several MFCs and was able to store the electricity generated from these MFCs to be able to light up a small Xmas tree.

Figure 6.1: Microbial fuel cell-powered lights on Xmas tree

With the scale-up MFC, we found that microbial fuel cells can scale-up to treat more COD or have a higher percentage of COD removed, but the energy production cannot be simply scaled up by manufacturing a larger microbial fuel cell. The voltage generated was about the same as a smaller, lab-scale MFC. Perhaps, more electricity can be generated by using a stackable microbial fuel cell or using several lab-scale MFCs.

Wang and Han (2008) found that stacking MFCs in parallel produced twice as much power as stacking them in series. Also, Cusick et al. (2011) constructed a pilot scale microbial electrolysis cell (MEC) fed with winery wastewater. This MEC reactor contained 144 electrode pairs in 24 modules. A MEC is a device similar to a MFC, but developed to convert wastewater into storable energy such as hydrogen or methane (Cusick et al., 2011).

6.2 Life Cycle Energy Comparison of Scale-Up Microbial Fuel Cell with DADS Landfill and Composting

The Colorado Convention Center spends approximately $15,500 per year to have their food waste hauled to A1 Organics (L. Smith, personal communication, March 2, 2011). In 2010, the Colorado Convention Center diverted 178.6 tons of food waste to be composted. The food waste was then combined with other waste to make Ecogro®, a Class I compost (A. Graff, A1 Organics, personal communication, February 22, 2011). In this way, the food waste is recycled, reused, and then has an economic value to be sold (per cubic yard) for landscaping. Lundie and Peters (2005) have explored the issue of food waste management options by comparing LCAs of a household sink processor, home composting, landfilling the food waste, and centralized composting. They found that centralized composting and landfilling are not the best options because of the energy-intense waste collection activities they require (transport to facility). Lundie and Peters (2005) concluded that home composting was the best option, but of course, this is not an option for the Colorado Convention Center because they most probably do not have the space for their own composting facility. This is a good segue into our research on a scale-up MFC that could be used as an on-site waste-to-energy system for the Colorado Convention Center.

The above discussion on composting and having an on-site food waste disposal system leads to our comparison of the scale-up MFC and DADS landfill LCAs. These life cycle energy analyses compare the energy conversion efficiencies for both

systems. The embodied energy consumed to operate a landfill such as the DADS landfill was much higher as shown by EIO-LCA as opposed to the energy produced from methane recovery resulting in an energy conversion efficiency of about 1%. On the other hand, the scale-up MFC also had an embodied energy consumption much higher than the energy output with a life-cycle based energy conversion efficiency of about 0.5%. However, it was found that it only takes the scale-up MFC one day (24 hours) to remove 70% of the COD while it takes a landfill a lot longer to reach the same percent COD removal.

The amount of energy in kilojoules per kilogram COD removed was a magnitude of 50 times higher for the scale-up MFC (6,860 kJ/kg COD) compared to the DADS landfill (84.3 kJ/kg COD). This is probably because the potential for energy conversion of a MFC is higher and it has a much lower COD loading than a landfill.

In summation, the energy input for a life cycle energy analysis conducted by EIO-LCA (which may overestimate the values) for both the DADS landfill and the scale-up MFC outweighed the energy output. However, the MFC cannot handle the amount of food waste generated by the Colorado Convention Center, while a landfill and composting center can handle approximately 180 tons per year. One would need to scale-up the MFC a lot more to handle that amount of food waste. Nevertheless, because the energy consumption and thus, the GHG emissions released, are so high for landfilling and centralized composting (mostly due to transportation and O&M), it would make sense that an on-site system would be the best option in terms of a LCA. Therefore, the next steps for this research would be to design an on-site pilot system for the Colorado Convention Center that would accurately portray the benefits of

having an on-site system in a LCA and would use a substance that is considered a waste to generate some carbon-neutral energy for the Colorado Convention Center.

In addition, some lessons learned that would be helpful for the design of a pilot scale reactor is that several MFCs in parallel work better than a large MFC, an air cathode MFC is the most cost-effective, and a gravity-fed reactor would reduce the energy needed to pump the food waste solution into the reactor. Also, it is useful to have a stock of reactor effluent with microbes already acclimated to food waste on hand to add to the food waste solution to improve performance or to jumpstart the reactor if there are operation and maintenance issues. This knowledge would have helped with the experiments for the scale-up MFC.

In conclusion, the Colorado Convention Center spends $15,500 annually on a system that hauls their food waste to another location, which as we can see uses a lot of fuel and releases carbon emissions into the air. Instead, they could use the funds above to manufacture about 28 scale-up MFC reactors ($560 each), which could use their food waste to generate electricity on-site. We recommend that the next steps for this research would be to design a pilot scale MFC to help the Colorado Convention Center reduce their waste and add to their use of carbon-neutral energy.

APPENDIX A. Calculations for Experiment Results

Below in Table A.1 are the simulated food waste (SFW) results for the first scale-up MFC manufactured that uses an external resistance of 1,000 Ohms.

Table A.1: SFW results for scale-up MFC with external resistance of 1000 Ω

Experiment	HRT (if applicable)	Maximum Power Density (mW/m^2)	Coulombic Efficiency (%)	COD Removal (%)
SFW Batch	--	2.54	1.6	78.5
SFW Continuous Flow	4.5 hrs	2.69	1.5	72.8

The amount of COD removal in a continuous flow experiment with recycle is shown below in Figure A.1. These results were also from the scale-up MFC with an external resistance of 1,000 Ohms. This graph shows that 70% removal for the scale-up MFC is at 24 hours. This experiment shows that the scale-up MFC can be operated with a recycle element that would lessen the water footprint of the reactor.

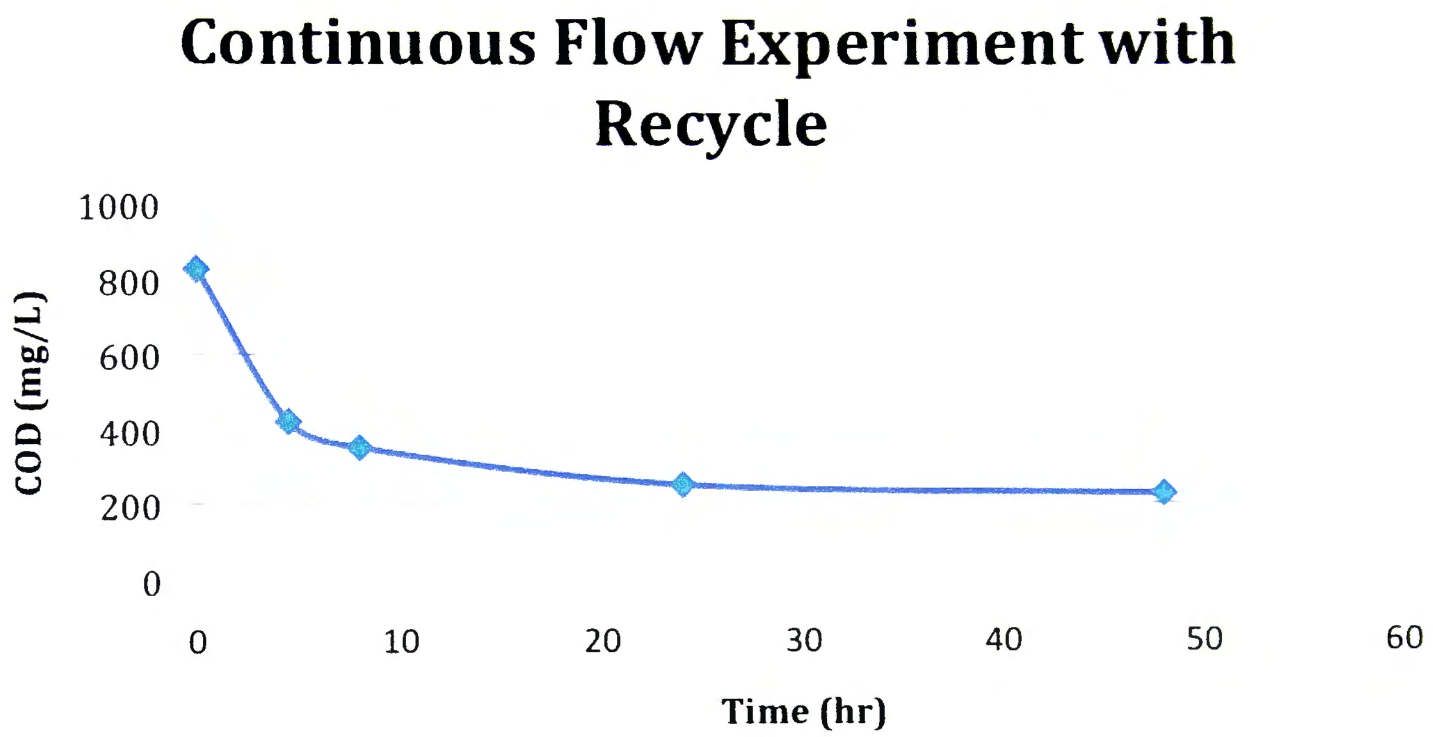

Figure A.1: COD results for a continuous flow experiment with recycle using scale-up MFC reactor with external resistance of 1,000 Ω

The COD removal, maximum power density, and CE were calculated using the equations in Section 4.1.2. The assumptions made were that the volume in the scale-up MFC was 1.5 liters and the volume of the holding tank was 2 liters so with a flow rate of 12 mL/min, the total HRT would be 4.5 hours. If the experiment was conducted without recycle, only the scale-up MFC volume was used, so since the HRT equals the volume divided by the flow rate, then the HRT using a flow rate of 12 mL/min would be 2 hours.

APPENDIX B. LCA Methodology

Below find the calculations for the life cycle assessment of the scale-up MFC and the comparison to the DADS Landfill.

LCA Methodology for DADS Landfill

1. **Energy input: EIO-LCA.** Construction, O&M, and transportation cost for landfill; used EIO-LCA to compute the energy input (one can also use to calculate GHG emissions released).
2. **Energy output: Total power production x (tons food waste/total tons of waste).** The 18,000 MWh per year produced by the methane recovery plant from the DADS landfill (Colorado SWANA, 2009) was multiplied by the ratio of tons of food waste (EPA-estimated national average of 14%) per year over total tons of municipal solid waste per year in the DADS landfill (City of Denver, 2011).
3. **Energy output per functional unit comparison: kJ/kg COD for one year.** The amount of energy from food waste for one year over 70% COD removal times tons of food waste in one year.

LCA Methodology for Scale-Up MFC

1. **Energy input: EIO-LCA.** Material costs were input into EIO-LCA and O&M (mixing and pumping) was calculated using average wattage multiplied by the time of energy input.
2. **Energy output: Electricity plus biogas (x 33% efficiency to convert to electricity).** $P = E^2/R = (0.4\ V)^2/(50\ \Omega) = 3.2\ mW$. Then converted to kWh (and GJ), after that one can use an emission factor of 1.75 lb CO_2e/kWh for Denver (Ramaswami et al., 2008) to get the GHG emissions displaced. Methane energy calculated in Chapter 4. The total electricity production calculated in Chapter 4 was then divided by 33% to get primary energy.
3. **Energy output per functional unit comparison: kJ/kg COD for one year.** The amount of energy from food waste produced in 24 hours x (365 days/24 hours) over 70% removal of food waste in 24 hours x (365 days/24 hours).

Table B.1 shows a calculation of energy from EIO-LCA. As you can see, EIO-LCA is a rough estimate of all the embodied energy that goes into a particular product or service in an industry sector. EIO-LCA can also calculate total GHG emissions released from the economic activity.

Table B.1: Economic Input-Output Life Cycle Assessment (EIO-LCA) example of energy calculation for the specific sector of waste management services (Carnegie Mellon, 2011)

Sector #562000: Waste management and remediation services
Economic Activity: $1.5 Million Dollars
Displaying: Energy
Number of Sectors: Top 10

Sector	Total Energy TJ	Coal TJ	Nat Gas TJ	Petrol TJ	Bio/Waste TJ	NonFossElec TJ
Total for all sectors	*7.97*	*1.48*	*1.98*	*3.49*	*0.256*	*0.760*
562000 Waste management and remediation services	2.14	0.011	0.387	1.54	0	0.200
221100 Power generation and supply	1.68	1.23	0.358	0.059	0	0.039
S00700 General state and local government services	0.833	0.008	0.250	0.575	0	0
324110 Petroleum refineries	0.387	0.000	0.103	0.251	0.019	0.014
331110 Iron and steel mills	0.227	0.135	0.062	0.002	0.001	0.027
481000 Air transportation	0.223	0	0	0.223	0	0.000
484000 Truck transportation	0.204	0	0	0.202	0	0.002
211000 Oil and gas extraction	0.201	0	0.164	0.017	0	0.020
325190 Other basic organic chemical manufacturing	0.161	0.020	0.061	0.022	0.048	0.009
492000 Couriers and messengers	0.150	0	0	0.148	0	0.002

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